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Relative Pose Measurement Algorithm of Non-cooperative Target based on Stereo Vision and RANSAC

[1*] CHEN Long, [2] GUO Bao-long, [3]SUN Wei
School of Mechano-electronic Engineering, Xidian University, Xi'an China
[1] *poulo125@126.com,* [2] *blguo@xidian.edu.cn,* [3] *sunweitom@tom.com*

Abstract. **The final approach phase of spacecraft rendezvous and docking is extremely important. In order to solve the problem of the real-time acquisition of the relative pose between target and spacecraft in near distance (<2m), this paper established a binocular stereovision model, and proposed a non-cooperative target relative pose measuring method based on stereo vision and RANSAC algorithm. Linear characteristic of Non-cooperative target was used to abstract feature points firstly, then stereo matching and 3-D restructuring were taken for the feature points, finally, an algorithm based on RANSAC algorithm was used to calculate the relative pose between the target and the camera. Therefore, errors were eliminated effectively, and the computation load was decreased by using disparity gradient constraint. Experimental results show that high accuracy and real-time results are the advantages of this method.**

Keywords: *Stereo vision, Non-cooperative target, Relative pose, RANSAC, Disparity gradient*

1. Introduction

Space non-cooperative target generally refers to the space objects which can't provide effective cooperative information, including fault or failure satellite, space debris, other party's spacecraft and so on[1]. It differs from cooperative target spacecraft rendezvous, since non-cooperative targets equips no target location marker or rendezvous sensor, which results in the incompleteness and imprecision of the observation information. Therefore, the gain of accurate relative navigation information is a key point in the accomplishment of non-cooperative target rendezvous.

At present, there're following measuring methods for non-cooperative target: (1) Image Matching. It establishes model according to the actual satellite, and match the existing model with collected satellite image to identify the target pose[2][3][17]. However, this method can be processed only when the shape and dimension of the satellite are known. (2) Image Flowing. This method adopts multiple images taken by monocular vision to measure the pose[4]. But it also requires certain prior knowledge, such as the specific geometric dimension or the proportional dimension of the satellite. Moreover, when the pose parameter is calculated, usually, solutions of nonlinear equations will be also involved, which complicates the computation. (3) Multi-sensor Method. It includes pose measurements such as by information fusion of laser range finder and monocular camera[5][13][14]. While its high cost, big volume and high power consumption disenable its usage when the measuring equipment is sensitive to the payload and power consumption. Besides, only one point on the target can be measured at one time by using this method, so it's very difficult to measure the target poses.

In view of the existing method requires a priori knowledge or need participation in the shortcoming, this paper proposed a relative pose measurement between spacecrafts based on stereo vision. Compared with monocular vision model, binocular one possesses many merits[15]: Binocular cameras can be used for data fusion in the stereo vision to enhance the robustness of the measuring precision and algorithm; It's free to any design of the marker, so there is no strict geometric restriction

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between markers; Binocular cameras can backup information from each other to increase the reliability of the measuring.

Since the target spacecraft is not equipped with cooperative marker, 3-D information of the target can be only gained according to its geometric characteristics. However, the extract of target's geometric characteristics could be influenced by calibration inaccuracy, light condition change and so on, errors can exist in the result of relative measuring. Therefore, this paper enhanced the precision of the relative pose measurement based on RANSAC algorithm, and computation speed was increased by pre-detection through disparity gradient constraint. The measurement proposed by this paper can still effectively eliminate gross errors, and accomplish high-precision relative pose measuring.

This paper is organized as follows: Section 2 introduces stereo vision principles and RANSAC algorithm principle. Section 3 explains the detailed processing steps of pose measuring algorithm based on stereo vision and RANSAC. Section 4 contains the experimental results and inaccuracy analysis. Finally, the conclusions are highlighted in section 5.

2. Stereo Vision and RANSAC

2.1 Camera Model and Definition of Coordinate System

In computer vision research, imaging model refers to the projection relationship on the image plane projected from the objects in 3-D space. The ideal projective imaging model, which is also called pinhole model, is the center projection in the science of optics. While pinhole projection is modeled by assuming all reflecting lights on the object are projected to the image plane through a certain point, that is, all rays are travelling in straight lines. Therefore, pinhole model can be used as camera imaging model.

In order to describe the camera imaging process quantitatively, Ow-XwYwZw (World Coordinate System), Oc-XcYcZc (Camera Coordinate System), Computer uv (Pixel Coordinate System) and O_T-$X_TY_TZ_T$ (Target Coordinate System) are set as Figure 1. The measured characteristic point is the O_T of the target coordinate system, and constitutes a right-handed coordinate system。

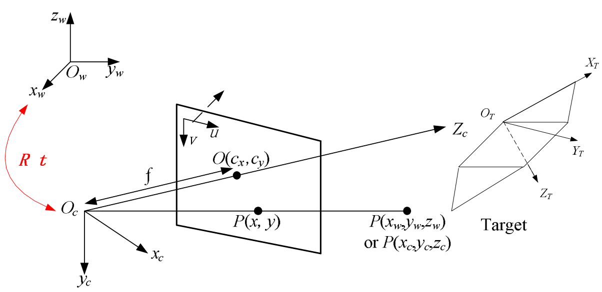

Figure 1. Definition of Coordinate System

2.2 Stereo Vision

As shown in Figure 2, P_1 is the image formed on the left camera C_1 by space point $P(X, Y, Z)$, with (u_1, v_1) as its coordinate on the image plane; P_2 is the image formed on the right camera C_2, with (u_2, v_2) as its coordinate on the image plane. If both left and right cameras are calibrated with M_1 and M_2 as their projection matrixes respectively, then:

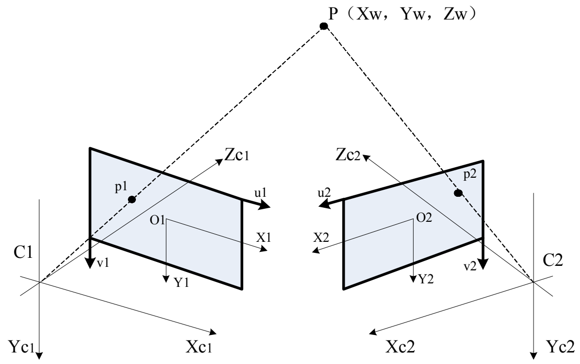

Figure 2. Stereo Vision Measurement

$$Z_{c1}\begin{bmatrix}u_1\\v_1\\1\end{bmatrix}=\begin{bmatrix}m_{11}^1 & m_{12}^1 & m_{13}^1 & m_{14}^1\\ m_{21}^1 & m_{22}^1 & m_{23}^1 & m_{24}^1\\ m_{31}^1 & m_{32}^1 & m_{33}^1 & m_{34}^1\end{bmatrix}\begin{bmatrix}X\\Y\\Z\\1\end{bmatrix} \tag{1}$$

$$Z_{c2}\begin{bmatrix}u_2\\v_2\\1\end{bmatrix}=\begin{bmatrix}m_{11}^2 & m_{12}^2 & m_{13}^2 & m_{14}^2\\ m_{21}^2 & m_{22}^2 & m_{23}^2 & m_{24}^2\\ m_{31}^2 & m_{32}^2 & m_{33}^2 & m_{34}^2\end{bmatrix}\begin{bmatrix}X\\Y\\Z\\1\end{bmatrix} \tag{2}$$

Z_{c1} and Z_{c2} can be eliminated by equation 1 and 2, and four linear equations will be gained:

$$\begin{cases}\left(u_1m_{31}^1-m_{11}^1\right)X+\left(u_1m_{32}^1-m_{12}^1\right)Y+\left(u_1m_{33}^1-m_{13}^1\right)Z=m_{14}^1-u_1m_{34}^1\\ \left(v_1m_{31}^1-m_{21}^1\right)X+\left(v_1m_{32}^1-m_{22}^1\right)Y+\left(v_1m_{33}^1-m_{23}^1\right)Z=m_{24}^1-v_1m_{34}^1\end{cases} \tag{3}$$

$$\begin{cases}\left(u_2m_{31}^2-m_{11}^2\right)X+\left(u_2m_{32}^2-m_{12}^2\right)Y+\left(u_2m_{33}^2-m_{13}^2\right)Z=m_{14}^2-u_2m_{34}^2\\ \left(v_2m_{31}^2-m_{21}^2\right)X+\left(v_2m_{32}^2-m_{22}^2\right)Y+\left(v_2m_{33}^2-m_{23}^2\right)Z=m_{24}^2-v_2m_{34}^2\end{cases} \tag{4}$$

Then, the coordinate （X_W，Y_W，Z_W） of P in world coordinate system can be calculated through least square method.

2.3 RANSAC Algorithm

Random Sample Consensus (RANSAC) algorithm was proposed by Fischler [9]. It's actually an iterative hypothesis-verification process: Firstly, the smallest subset is selected randomly from the input data set to estimate parameter initial value of the model, and parameter value of the equation is iteratively estimated. Then, data is divided into Inliers and Outliers by using these initial parameter values. Finally, all Inliers are used for re-calculating and re-estimating the parameter of the equation. If the hypothesis is verified to be true, there must be abundant inliers. Effective consensus set with enough inliers will be found by repeating the above process, then, the model parameter can be re-estimated by using all the inliers inside the effective consensus set. RANSAC algorithm minimized the influence of noise and outliers on the computation, and to some extent reduced computational load. RANSAC algorithm process as follow:

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(1) Calculate the number of samples M by equation (5) according to confidence probability P and data error rate ε as well as the minimum data quantity needed for the computation of model parameter;

$$1-(1-(1-\varepsilon)^m)^M = P \tag{5}$$

(2) Randomly select initial data for sampling, and computer the corresponding model parameter for each selection, the number of samples in each selection is the minimum data quantity needed for estimating model parameter;

(3) Verify the model parameter with all initial data to gain the number of inliers of each model parameter; repeat step (2) and step (3) until the manipulation of M selections of samples is completed.

(4) Select optimal model parameter according to the number of inliers and the variance of errors;

Find all inliers corresponding to the optimal model parameters, and calculate the final model parameter by using these data.

3 Relative Pose Measurement Based on RANSAC

3.1 Relative Pose Measurement

The method flow chart of relative pose measurement based on stereo vision proposed by this paper is shown as Figure 3. As for extracting of characteristic points, this paper adopted the method stated in reference [7]: Since most of the non-cooperative targets are cubes and quipped with attachment bracket, that is, there's at least one rectangular surface or triangular surface on the target, edges can be extracted through Canny edge detection algorithm in the left image, and edge linear equation can be obtained by using Hough Transformation, then, space characteristic points will be unveiled, and the points tracked in subsequent frames[17]. After the computer pixel coordinates of the space characteristic points (u_1,v_1) and(u_2,v_2) are located in both left and right images, the 3-D coordinates of the space characteristic points can be gained by solving equations (3) and (4) through least square method.

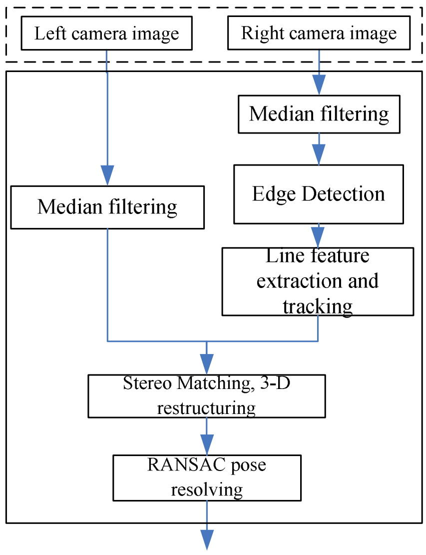

Figure 3. Relative Pose Measurement Based on Stereo Vision

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After the 3-D coordinates of the characteristic points on the target are determined in the O_W-$X_WY_WZ_W$, O_T-$X_TY_TZ_T$ should be established for calculating the relative poses between the two systems, and furthermore, the relative poses between the space target and the tracking satellite will be exposed [10]. Suppose the coordinates of a space random point P in the two coordinate systems are (X_W, Y_W, Z_W) and (X_T, Y_T, Z_T) respectively, the relationship between the two coordinates is shown as follows:

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = k\boldsymbol{R}_{wT} \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} + \boldsymbol{t}_{wT} \tag{6}$$

Where R_{WT} represents the spin matrix from O_W-$X_WY_WZ_W$ to O_T-$X_TY_TZ_T$, t_{WT} shows the translation vector from O_W-$X_WY_WZ_W$ to O_T-$X_TY_TZ_T$, and k denotes zoom factor.

Suppose the coordinate vector of each characteristic point in O_T-$X_TY_TZ_T$ is P_{Ti} (X_{Ti}, Y_{Ti}, Z_{Ti}) ($i=1,2...N$) , and 4 of them are P_{T1}, P_{T2}, P_{T3}, and P_{T4}. If three of the four points are not in the same line, P_{T1}-P_{T2}, P_{T3}-P_{T1}, (P_{T2}-P_{T1}) × (P_{T3}-P_{T1}) are nonlinear, then:

$$A_T = \left[P_{T2} - P_{T3} \quad P_{T3} - P_{T1} \quad (P_{T2} - P_{T1}) \times (P_{T3} - P_{T1}) \right] \tag{7}$$

In a similar way, the following can be gained in the Ow-XwYwZw:

$$A_W = \left[P_{W2} - P_{W3} \quad P_{W3} - P_{W1} \quad (P_{W2} - P_{W1}) \times (P_{W3} - P_{W1}) \right] \tag{8}$$

Since the relative poses between rigid transformations characteristic points are constant, then:

$$A_T = R_{WT} A_W \tag{9}$$

Therefore:

$$R_{WT} = A_T A_W^{-1} \tag{10}$$

Suppose the element of R_{WT} is defined as $\delta_{ij}(i, j = 1,2,3)$, the estimated formulae of elevation angle θ, yaw angle ψ, and roll angle Φ can be gained as follows through coordinate system conversion formula [12]:

$$\begin{aligned} \theta &= \arcsin(\delta_{13}) \\ \psi &= \arcsin(\frac{\delta_{11}}{\cos\theta}) \\ \phi &= \arcsin(\frac{\delta_{23}}{\cos\theta}) \end{aligned} \tag{11}$$

According to the self-structure characteristics of the non-cooperative target, the target model can be simplified into characteristic-point model, then, algorithm can be determined based on characteristic point vision so that the relative pose parameter of the non-cooperative spacecraft can be computed. In order to eliminate the influence of gross errors caused by mistaken characteristic-point extracting or mistaken characteristic-point matching, RANSAC algorithm will be used so that precise relative pose parameter can be calculated.

Since the computation load of RANSAC algorithm is quite large, pre-verification should be done before transformation model computation. Only verified models can be re-estimated and re-verified. In this way, computation time is greatly saved.

3.2 Disparity Gradient Constraint

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In this paper, disparity gradient constraint is adopted for pre-verification. The two adjacent characteristic points *m* and *n* in one image match with *m'* and *n'* in another image according to the definition of disparity gradient. If they're compatible with each other, the disparity gradient G_d should be less than or equal to 2. If the disparity gradient is over 2, the two characteristic points are considered unmatched.

$$G_d = 2\frac{\|(m'-m)-(n'-n)\|}{\|(m'-m)+(n'-n)\|} \tag{12}$$

Where (m', m) and (n', n) represent image coordinate vectors of the corresponding characteristic points, $\|p\|$ indicates the module of vector p.

3.3 Algorithm Processes

The processes of relative pose algorithm based on RANSAC show as follows:

(1) Calculate the number of samples M by equation (5) according to confidence probability P and data error rate ε;

(2) Provided $X_{Wi}(i=1...N)$ and $X_{Ti}(i=1...N)$ represent the homogeneous coordinate vectors of N (N>4) characteristic points on the target in World Coordinate System and Target System respectively, randomly select three nonlinear points to form a sample;

(3) Compute the disparity gradient G_d between the three points, if G_d is over 2, repeat step (2); otherwise, move to step (4);

(4) Calculate the spin matrix R_{WT} of the Target Coordinate System relative to World Coordinate System according to equation (10);

(5) Randomly select one point from the rest points, and compute residual error ε between the point and matrix R_{WT} according to equation (13);

$$\varepsilon = \|X_T - R_{wT}X_w\| \tag{13}$$

(6) Define the threshold value as T1: if ε <T1, the three points selected in (2) are considered as inliers; if ε⩾T1, the three points selected in (2) should be outliers;

(7) Repeat step (2) to step (6) until the manipulation of M selections of samples is completed;

(8) Re-estimate R_{WT} according to the inliers gained from consistent set;

(9) Compute the elevation angle θ, yaw angle ψ, and roll angle Φ according to R_{WT}.

4 Experiment Results

An experimental platform is established to complete the measuring experiment of moving targets, and a certain spacecraft model is selected as target spacecraft. The target is moving forward with a uniform speed of 0.1m/s, and simulates the slight horizontal and vertical vibration caused during rendezvous. The measuring system used is shown in figure 4

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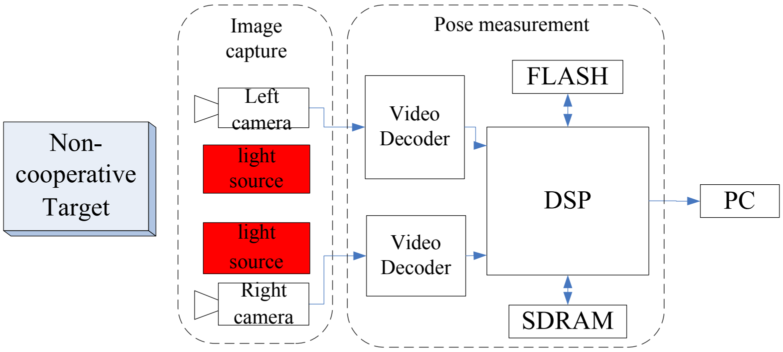

Figure 4 . System block diagram

The following show the parameters of the left and right cameras: focus length 0.012m, pixel size 16μm×14μm, and image size 720×576.

Figure 5 shows the image pair of the measured moving target generated at a certain moment. If the measuring results of 100 frames of images are selected during measuring, the coordinate of one point (the bottom center of the triangular bracket, namely, the actual gripping point) in World Coordinate System can be obtained as table 1. Measurement error is shown in figure 7.

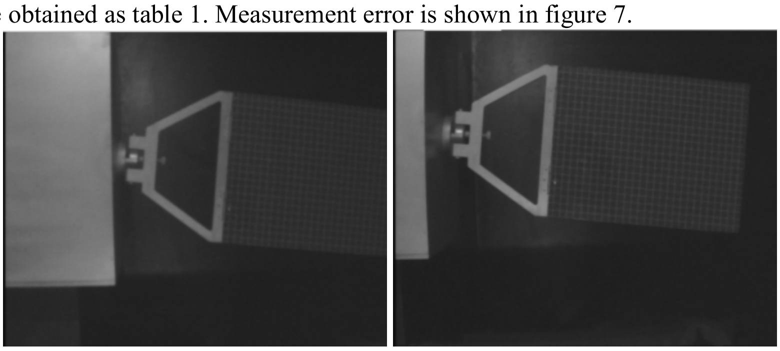

Figure 5. Left and Right Images of the Measured Target

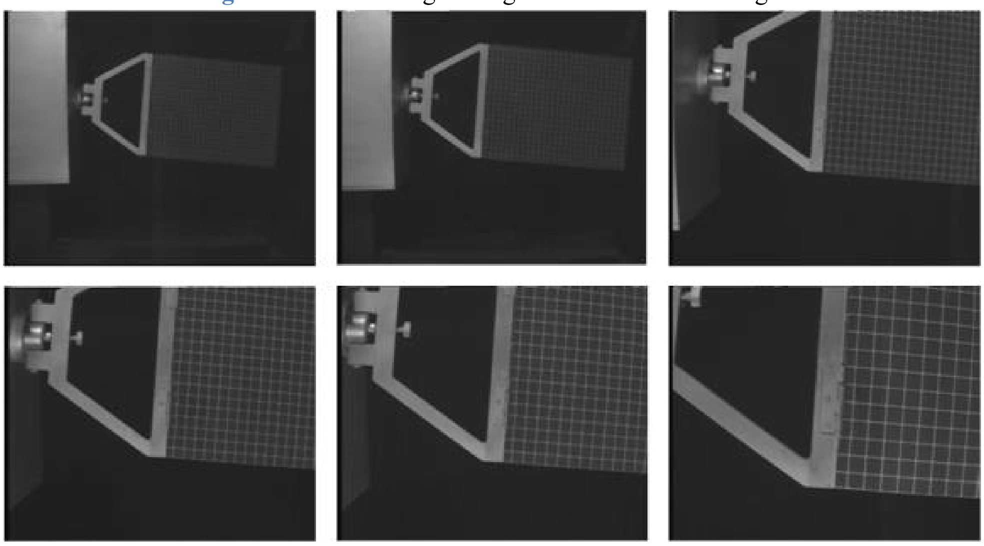

Figure 6. Moving Video Sequence of the Pending Satellite

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Table 1. Result of Measurement

	Measured value	**Actual value**	**Error**
X_W	0.207m	0.220m	-0.013m
Y_W	0.047m	0.040m	0.007m
Z_W	1.859m	1.800m	0.015m
θ	0.33°	0°	0.33°
ψ	-21.8°	-21°	-0.8°
Φ	54.98°	55°	-0.02°

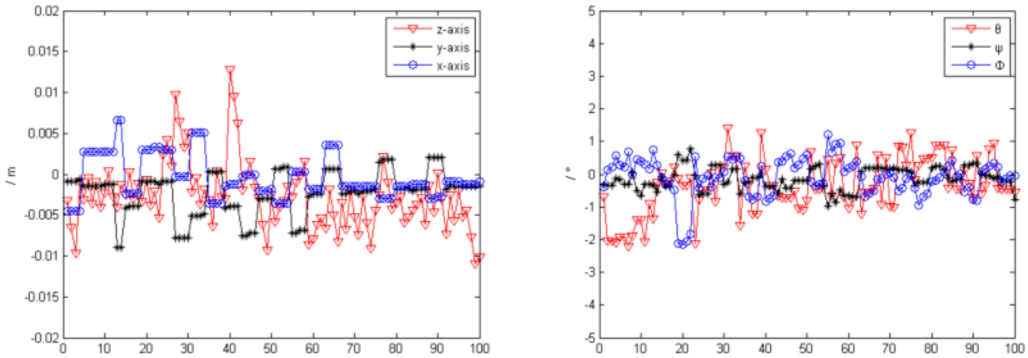

Figure 7. Measurement Error Curves

The measuring result suggests that, by using the measurement proposed in this paper, the accuracy of the relative pose measurement can up to ±0.02m, the precision of the relative attitude measurement can be within 2°, and the measuring speed can reach 15 frame/s, which basically satisfies the requirements of non-cooperative target measuring.

While the following shows the main reasons which influence feature point positioning accuracy:

1. Camera calibration accuracy: equation (3) and (4) show that the 3-D restructuring of the feature points depends on camera’ s projection matrix M, which includes both internal and external parameters, and can be gained through camera off-line calibration, therefore, calibration accuracy directly affects the measuring accuracy of the relative position.

2. Parameter choose of Hough transform: due to heavy computation of Hough transform, and in order to realize real-time calculation, the steps of parameter θ and ρ shouldn’ t be too small. As a result, the accuracy of the straight line extraction is influenced.

3. Influence of camera shake: camera will shake slightly during the relative motion, while electronic image stabilization process wasn’ t involved in the measuring of this paper, so consequent shake would also exist between image frames captured. Hence, accuracy is reduced.

5 Conclusion

This paper proposed a measuring method based on stereo vision and RANSAC algorithm in order to measure the 3-D pose of the non-cooperative target. Then, semi-physical simulation is adopted to measure the moving target. The result of the measurement shows this algorithm can provide high real-time and precise services, and meet the needs of non-cooperative target rendezvous measurement. Next work will focus on non-linear high-accuracy camera calibration algorithm, adaptive feature point extraction algorithm, as well as fast electronic image stabilization algorithm, so as to further improve the accuracy and real-time performance.

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